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A minimum data set for assessing soil quality in rangelands

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Abstract

To develop a method for the selection of suitable predictive indicators for the assessment of soil quality, we used a general approach for choosing the most representative indicators from large existing data sets, for mountainous rangeland in northern Iran. The approach involves identifying a suite of soil indicators and landscape attributes for an area of relatively uniform climate. The interrelationships between soil properties and plant growth in various landscape units were investigated and interpreted based on statistical analysis and expert knowledge. Multivariate statistical techniques were used to determine the smallest set of chemical, physical, and biological indicators that account for at least 70% of the variability in the whole soil data set at each site. We defined this set as the minimum data set (MDS) for evaluating soil quality. Using investments of time and budget considerations, two minimum data sets were selected. The MDSs were selected for their ability to predict soil stability and productivity, as components of site potential assessment for extensive grazing. The efficacy of the two chosen MDSs were evaluated in terms of their capacity to assess range capability by performing multiple regressions of each MDS against the plant growth characteristics: total yield, herbaceous plant production, and utilizable forage as iterative dependent variables. Variations in the plant response variables were best predicted by the variables, soil profile effective thickness, followed by nutrient cycling index, which is a landscape function indicator; total nitrogen; slake test; first layer thickness; and water retention at wilting point. The relationships between soil properties and plant growth showed that plant variables were more sensitive to soil physical properties than to soil chemical properties.

Keywords: Soil quality index; Soil physical properties; Soil chemical properties; Rangelands; Principal components analysis

1. Introduction

Rangeland is an economically and culturally important enterprise in the mountainous regions of Iran, as it is elsewhere in the world. Assessment of rangeland capability and function is necessary to prevent resource degradation and to facilitate adaptive management practices. Science-based indices of soil quality (SQIs) provide the necessary information for land managers to make informed decisions. Considering basic soil functions, i.e., provision of sufficient amounts of water and nutrients, provision of resistance and resilience to physical degradation, and sustaining plant growth under appropriate management, numerous soil analyses might be required to fully characterize the soil/plant system. Using a minimum data set (MDS) reduces the need for determining a large number of indicators to assess soil quality. To identify the smallest number of

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measurable soil properties that define the major processes functioning in soil, several MDSs have been proposed (Larson and Pierce, 1991; Doran and Parkin, 1996; Andrews and Carroll, 2001). The above-mentioned MDSs often include many auto-correlated properties, are tedious and costly to collect, and sometimes are not specific to assessment of rangeland capability. With respect to landform using statistical analyses operating upon soil properties, we presented a method for the selection of suitable indicators for the assessment of SQ for semi-arid rangeland in Iran.

2. Study system and data generation

2.1. Site description

The data were collected from 234 land unit tracts (LUT) in the Lar aquifer, which is between 35°4′36″ and 35°48′40″ north and 51°32′ and 52°4′ east 78 km north of Tehran, Iran. The climate is semi-arid with a mild summer and very cold winter (Iranian Meteorological Organization, 2001). The mean monthly temperature ranges from −6.5 °C in January to 18.4 °C in July. The mean annual air temperature is about 7 °C. The Lar precipitation pattern is a Mediterranean regime (Soil and Water Research Institute, 1978). The annual mean precipitation is 496 mm, which mostly falls during winter and springs (November–May).

Based on U.S. Soil Taxonomy (USDA-NRCS, 1998), the study area is occupied by lithic and typic xerorthents, typic haploxerecpts, and fluvaquents. To carry out this research, three major plant community types[1] (herb, shrub–grass, and grass) consisting of fifteen different vegetation types[2] were identified; three of which: *Bromus tomentellus–Astragalus microcephalus* (sub-area I); *B. tomentellus–Onobrychis cornuta* (sub-area II); and *Agropyron repense–Chaerophyllum macrospermum–Ferula galbaniflua* (sub-area III) were chosen for this research. Each sub-area represents different geological mapping units. Each sub-area has different geology. Sub-area I consisted of shale, sandstone, and limestone with subordinate sandstone. Sub-area II has predominantly thick-bedded green tuff, tuffaceous shale, marl, and conglomerate; while in sub-area III thick-bedded limestone is prevalent (Vahdati Daneshmand, 1997).

[1] Plant community type is defined as: An aggregation of all communities with similar structure and floristic composition. A unit of vegetation within a classification with no particular succession status implied.

[2] Vegetation types: A kind of existing plant community with distinguishable characteristics described in terms of present vegetation that dominates the aspect or physiognomy of the area.

2.2. Experimental design

The stratifying procedure was conducted using vegetation type maps and 1:50,000 scale topography maps. A factorial completely randomised design considered three vegetation types, two elevation classes (2500 to 2800 m and 2800 to 3100 m), four general aspects (north, south, east, and west), and five slope classes (0–3%, 3–10%, 10–32%, 32–56%, >56%) comprising a total of 120 possible LUT ($3*2*4*5=120$) combinations. Taking into account three replicate sites for each LUT, with replicates located in different locations within the study area, 360 sample sites could be identified, however only 234 were found and sampled.

2.3. Soil sampling and laboratory analyses

To determine soil chemical properties, the samples were collected from a total of 234 transects within stratified land units. The position of each transect line was oriented parallel to the general slope in the middle of each land unit. Soil samples for determining chemical properties were collected from the top 10 cm of soil within 4 plots of 0.5 m^2, which were located at 6, 12, 18, and 24 m along the 30 m line transect. The samples were passed through a 2 mm sieve. The fine earth fraction (<2 mm) was retained for chemical analysis. Soil pH was determined using an electrode pH-meter for a saturated soil paste using deionised water (McLean, 1982). The electrical conductivity was measured in the saturated paste extract (Rhoades, 1982). Organic carbon was determined using the Walkley-Black method (Nelson and Sommers, 1982). Total nitrogen was measured using the Kjeldahl method (Bremner and Mulvaney, 1982). To determine exchangeable potassium, the neutral 1 N ammonium acetate extraction method was used (Knudsen et al., 1982). The Olsen method was used to determine extractable phosphate using a molybdate reaction for colorimetric detection (Olsen and Sommers, 1982). Cation Exchange Capacity was determined for soil samples from 40 LUTs by replacement of exchangeable cations by ammonium acetate (Thomas, 1982). These samples were collected from different land units randomly. Sodium Absorption Ratio was calculated using analyses of saturated paste extract for sodium (Na^+) by flame photometry, and calcium (Ca^{2+}) and magnesium (Mg^{2+}) by compleximetric titration using ethylenediaminetetraacetic acid (EDTA) (U. S. Salinity Laboratory Staff, 1954).

To determine soil physical characteristics, we dug a 150 ∗ 70 cm pit, to the depth of a hard layer but not deeper than 150 cm, in the middle of each LUT (N = 234). Profile description focused on the nature of soil materials and was based on criteria in the Australian Soil and Land Survey Field Hand Book (Gunn and Aldrick, 1988). To assess soil structure, abundance, size and shape and grade of structure were evaluated. The soil profile effective thickness (SPET) was defined as the equivalent soil depth consisting of <2 mm particles (Rezaei, 2003).The first layer thickness (FLT) was defined as the soil that extends from the surface down to the top of the B horizon, including the A and AB horizons (or A and E horizons) (Benny and Stephens, 1985). First layer effective thickness (FET) is the first layer thickness excluding coarse fragment content. Particle size analysis was by the hydrometer method for each layer (Rezaei, 2003). Particle size was used to develop a predictor of soil water retention capacity for matric pressures of 0.33 bar (field capacity) and 15 bar (wilting point) using a pedotransfer function (PTF) (Rezaei, 2003).

2.4. Sampling for yield measurement

We measured total current year production (TY) and production of herbaceous plant (HP), and estimated utilizable forage (UF). We used the direct harvesting technique; because it is considered to be the most reliable method of determining above ground biomass (Bonham, 1989; Holechek, 1995). Harvest for yield production occurred at flowering of the dominant species in each vegetation type (sub-area). The grasses and forbs were all clipped to ground level. For yield production of the spiny plants, such as *A. microcephalus* and *O. cornuta*, only the current seasonal growth of each plant was estimated through measuring a proportion of samples for the dominant species. Spiny plant production was subtracted from TY to calculate HP. Species were also sorted into the three categories, palatable (class I), semi-palatable (class II), and unpalatable species (class III), to calculate an index of UF (Moghaddam, 1998).

2.5. LFA data collection

The Landscape Function Analysis (LFA) method (Tongway and Hindley, 1995, 2004) considers rangelands as landscape systems. Landscape organization index (LOI) is defined within the LFA procedure as the arrangement of zones that reflect run-on and run-off processes. Using the LFA method, we derived values for an LOI and three other soil surface indices: Soil Stability index (SI), Infiltration index (Infil), and Nutrient Cycling index (NCI). The indices included relevant combinations of individual soil surface features, comprising soil cover, litter cover, cryptogam cover, crust brokenness, erosion features, deposited material, microtopography, slake test, and soil surface texture (Tongway and Hindley, 1995, 2004). The landscape organization data were collected for each LUT along the line transects.

3. Indicator selection

We selected two MDSs by a procedure that used two different combinations of indicators. The MDS1 included only soil chemical and physical properties; and MDS2 utilized soil properties and landscape function analysis indices.

Step 1: We used Pearson correlation coefficients to determine the eligible dependent variables for inclusion in the second step. Those soil properties that did not show a strong relationship, a Pearson correlation coefficient <0.50, with site potential characteristics (TY, HP, and UF), were eliminated from the data list.

Step 2: Principal Component Analysis (PCA) was employed as a data reduction tool to select the most appropriate indicators of site potential for the study area from the list of indicators generated in Step 1. Only the PCs with eigenvalues >1 were considered for identifying the MDSs. Within each PC, indicators receiving weighted loading values within 10% of the highest weighted loading were selected for the MDSs. When more than one variable was retained within a PC, the correlations sum were examined to determine if any variable could be considered to be redundant. It was assumed that highly weighted variables were highly correlated, if their linear correlation (r) was >0.70.

Step 3: Multiple regression analysis was considered to be an appropriate tool to assess how well the selected minimum data sets represent range capability (site potential). These analyses were performed using component values of the two final proposed minimum data sets, MDS1 and MDS2, as independent variables and measured plant growth characteristics as response or dependent variables. Three measurable characteristics of site potential characteristics namely total yield production (TY), yield production of only herbaceous plant (HP), and utilizable forage (UF) were used as response variables to evaluate the proposed MDSs as explanatory variables.

4. Results and discussion

4.1. Step 1: Eliminating unimportant variables

Based on the results of conducting Step 1, the variables pH and SAR were eliminated, as they were not well correlated with TY, HP, and UF (Table 1). Probably the range of values for those properties within the study area is insufficient to result in substantial differences in plant growth. The effects of other eliminated variables including clay, silt, and sand content, and structural porosity index have effectively been taken into account in the calculation of water retention capacity (Rezaei, 2003).

4.2. Step 2: Selecting important variables

Considering the criterion for the original soil data set (PCs receiving eigenvalues >1), the first three PCs explained more than 82% of variation in the potential MDS1 indicators (Table 2). More than 77% of the variation among all original data sets including soil properties and LFA indices was explained by the first three PCs in the PCA run for MDS2 selection (Table 2). The principal component loading matrix (Table 2) shows that the first PC for MDS1 selection had five highly weighted variables within 10% of the highest factor loading. All five were also highly correlated. The five indicators were FET, SPET, CFr, FC, and AW. This group of indicators implies that this first PC is mainly associated with soil water retention capacity. For inclusion in MDS1, SPET, which has the highest factor loading (Table 2) and correlation sum (Table 3), were chosen to represent the first PC. For the second PC, EC, OC%, N%, and exK were within 10% of the highest factor loading. This group of four attribute relates mainly to soil chemical fertility. Due to its highest correlation sum, N% was retained as the most important factor from this PC to be included in MDS1 (Table 3). In the third PC for MDS1 selection, FLT, ST, and GP were within 10% of the highest factor loading. The pattern and size of loading factors show that this PC is mainly concerned with soil stability. The slake test (ST) was eliminated because it is highly correlated with grade of pedality (GP). Therefore, FLT and GP were selected as representatives of the third PC inclusion in MDS1. Overall, the indicators selected for MDS1, comprising only soil chemical and physical properties, were SPET, N%, GP, and FLT.

The first PC for MDS2 was mainly associated with soil water storage (CFr, SPET, FET, FC, and AW) and nutrient pool factors (NCI). The highly weighted variables related to water holding capacity were also all highly correlated with SPET (Table 2) and thus were considered to be redundant. Of this group, SPET was selected for the MDS2 as the representative of the entire water holding variables group based on its having the highest correlation sum and the highest loading factor. NCI was retained as the representative of the nutrient pool. The proximity of loading factor sizes for SPET and NCI confirms the statement of Benny and Stephens (1985) that SPET is an important parameter in determining soil functions relating to storage of both plant available water and nutrients. From the second PC, water retention at FC and WP received the highest loading factors, which were highly correlated (Table 2). The water retention at WP has been selected as the representative of the second PC to be included in MDS2. In the third PC, two groups of variables received high factor loadings: a nutrient pool group and a soil stability group. The nutrient group consisted of OC%, N%, and exK. The stability variables were ST and stability index (SI). Of the nutrient variables, N% has the highest correlation sum (Table 3). However, the absolute value of the loading factor for exchangeable K is higher than for N%. In addition, the correlation between N% and NCI (an indicator selected under PC 1) is much higher (R=0.69) than correlation between exchangeable K and NCI (Table 1), making exK the less redundant choice for an indicator of nutrient availability in third PC. The NCI, which is an integrative index, is correlated with the concentrations of OC% and total N%. Therefore, having NCI together with exK in the data set instead of N% or OC% can identify aspects of soil fertility other than those represented by OC% and N%. However in the absence of data for exK, the total N data can be recommended as the best surrogate for exK to predict plant growth measurements. For the stability indicators, the absolute factor loading for stability index (SI) was higher than for ST (Table 2). However, due to a higher correlation sum for ST (Table 3) and closer relationships between ST and site production variables compared with SI, ST was chosen as the representative of stability function for MDS2. Finally, the indicators selected for MDS2, comprising soil chemical and physical properties accompanied by landscape function indices (LFA), were NCI, SPET, exK, ST, and WP (water retention capacity at wilting point).

4.3. Step 3: Testing the MDS through multiple regression analysis

The multiple regression functions for all plant growth characteristics i.e., TY, HP, and UF, involved all 4 proposed variables within the MDS1. The most predictive model for HP explained more than 72% of the variation. The model for TY was slightly less predictive (coefficient of determination (R^2) = 0.67), which is reasonable, because production of non-herbaceous plants, e.g., *O. cornuta* and *A. microcephalus* with long roots partly depend on water and nutrients within a soil column deeper than the 150 cm depth investigated in this research. The major factor associated with variation in all plant response variables was SPET, which has a close relationship to the water holding capacity. After SPET, total nitrogen percentage explained most of remaining variation for all response variables. In contrast to TY (R^2 = 0.67) and HP (R^2 = 0.72), the model for UF is less predictive, (R^2 = 0.59). The major reason for this difference may be that the utility of forage is strongly dependent on plant palatability, which in turn is dependent on plant species, i.e., plant genus, plant inherent palatability, and range management rather than only on site inherent productivity.

The stepwise multiple regression functions for predicting TY and HP using MDS2 involved all 4 proposed variables within MDS2. However for UF only three variables, i.e., NCI, SPET, and ST, were included in the model. The predictions have been plotted as predicted versus measured values for TY, HP, and UF. The most predictive model was that for yield production of HP, which explained 83% of variation followed by the model for TY, which explained 80% of total yield variation (Fig. 1). The least predictive model was for UF which explained only 64% of variation (Fig. 1). The major factors associated with variation in all response variables were NCI followed by SPET.

5. Conclusion

The MDSs were utilized for soil quality assessment with respect to the management goals of soil productivity and stability. Depending on the required accuracy, time restrictions, and budget either MDS1 or MDS2 could be employed for rangeland capability assessment. By taking into account landscape function indices, MDS2 provides a better prediction of range production; if there are no limitations on budget and time it is better to use MDS2 components to predict soil productivity and stability in rangelands. The MDS2 components describe most of the soil basic functions including: (1) the ability to accept, hold, and release water to plants, (2) maintain productivity (3) and to respond to management and resist degradation. Similarly, comparison of the MDSs, with and without landscape function analysis indices, showed that the proposed MDSs, especially MDS2, are consistent with the conceptual basis of LFA which includes (1) the soils ability to absorb and store rainfall, (2) the soils ability to store and cycle nutrient elements, and (3) the soils resistance to erosion. NCI as an integrative variable explains variation in soil productivity for rangelands better than does any other single variable.

The method described in this paper has been designed for selecting the most appropriate soil properties for assessing soil quality and the potential of rangelands in alpine semi-arid areas of Iran. We expect there will be no difficulty in application of this approach to areas with different plant communities, climates or soils; however, use of the selected components of MDSs from this study to other parts of the world may require adjustments to both the data sets and scoring of the components of MDSs.

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